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THE AURA FATIGUE AND HEAT STRESS ALGORITHMS

J. TERRENCE KLOPCIC

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Since its inception in the late 1970's, the Army Unit Resiliency Analysis Methodology has been applied in an increasingly wider array of studies dealing with unit performance on the conventional/nuclear/chemical battlefield. These applications have resulted in many methodology expansions. In particular, highly detailed models of personnel response have been added with the assistance and in support of the medical community. This report describes, in fair detail, the fatigue and heat stress models and presents corroborating data and calculations. These models have been extensively used and are supported by results of field exercises.

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I. INTRODUCTION

AURA, the Army Unit Resiliency Analysis, is an event sequenced, one-sided combat simulation methodology. The methodology consists of an (expanding) number of highly detailed models from the various technical communities interfaced into a large, time-dependent event playing and optimization routine. The interfaces are varied, involving such diverse kill probabilities as lethal footprints for conventional munitions, log normal kill probabilities for nuclear effects, toxic chemical dispersions and evaporations, MOPP degradation, reliability, and target acquisition probabilities. The optimization is a dedicated, non-linear routine which models the (commander's) reallocation of surviving, degraded assets in order to minimize the choke points in the optimal functional path. The logic process required the development of a general model for the functional structural of a military unit: Such a model was developed and forms an essential part of the AURA methodology.

Since its inception in the late 1970, AURA has been applied in an increasingly wider array of studies, particularly those dealing with unit performance on the integrated (conventional, chemical, nuclear) battlefield. Under the BRL philosophy regarding AURA, the methodology has expanded to meet the needs of new applications that are consistent with AURA's remaining a one-sided, unit-level model. Many of these expansions, particularly those done for the medical community, have involved the insertion of highly detailed models of personnel response to battlefield environments. Two of these have involved models for fatigue and for heat stress in soldiers wearing chemical protective ensembles. The purpose of this report is to describe those models.

Both the fatigue and heat stress models have been previously described in internal, unpublished reports.[1] [2]

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[1]J. Terrence Klopcic, *The Modeling and Operation of Fatigue in AURA,* 1988 (UNCLASSIFIED)

[2]J. Terrence Klopcic, *The Correlation and Modeling of Job Performance Degradation and Heat Stress Probability Due to the Wearing of Chemical Protective Apparel,* 1985 (UNCLASSIFIED)

II. THE MODELING AND OPERATION OF FATIGUE IN AURA

A. Introduction

Current perceptions of the modern battlefield are dominated by sustained operations conducted "around the clock". In such an environment, fatigue becomes a factor of overwhelming importance. This is especially true for units not in direct contact with opposing forces: Although the intensity of present day direct fire weaponry may limit the amount of time that maneuver units will actually be engaged, the activities that support the maneuver units (fire support, logistics, medical, etc.) will be conducted without stop.

In light of this growing importance, the Ballistic Research Laboratory, developer and custodian of the Army Unit Resiliency Analysis (AURA) Methodology, has reviewed and, with the help of the Walter Reed Army Institute of Research (WRAIR), improved the fatigue model in AURA. In fact, the fatigue model in AURA had been used several years ago in a TRASANA (now TRAC-WSMR) study of sustained operations.[3] The technical assistance provided by COL Belenky and LTC Hursh of WRAIR improved the sleep model and provided improved values for some of the model parameters while confirming the overall functional behavior of the algorithms.

The purpose of this treatise is to describe the fatigue and rest algorithms in AURA. It will be assumed that the reader has some familiarity with the AURA methodology. Therefore, little effort will be spent in describing the extensive logic and algorithms involved in allocating individual capabilities to specific tasks and combining those tasks into unit mission performance. For more information on that subject, the reader is directed to the appendices in the user's manual.[4]

B. Restedness and SLUNIT Accumulation

In order to quantify the state of restedness and the benefits of sleep, a unit of sleep, called the SLUNIT, was invented. Although the SLUNIT is, strictly

[3] Mr. Daniel Belk and Mr. Phillip Billingsley, TRAC-WSMR, private communication

[4] J. Terrence Klopcic, *Input Manual for the Army Unit Resiliency Analysis (AURA) Methodology: 1988 Update*, Ballistic Research Laboratory Report BRL-TR-2914, May 1988. AD # A196-266 (UNCLASSIFIED)

speaking, an abstract concept whose value can be adjusted to best fit the existing data, a SLUNIT can be roughly equated to the recuperative value of one minute of efficient sleep. (The term "efficient sleep" is defined below.) Thus, accumulated SLUNITs are a measure of an individual's restedness. SLUNITs can be accumulated by an individual up to a maximum (CEILING), which corresponds to being fully rested. That maximum may, in fact, be a highly individual quantity; AURA therefore provides for user inputs for CEILING values for each individual in the simulation. As a default value, AURA currently uses a CEILING of 1520 SLUNITs for everyone. (The derivation of 1520 is shown in Appendix A.)

One of the recent improvements to AURA was to better define the SLUNIT accumulation algorithm. Studies conducted by Belenky[5] of WRAIR indicate that the first ten minutes of sleep have little recuperative value. During the subsequent twenty minutes, sleep efficiency improves, reaching a maximum efficiency at approximately thirty minutes. From thirty minutes until the fully rested state is approached, sleep is fully efficient. In terms of the AURA model, accumulation during this period is at the rate of 1 SLUNIT/minute. (Note: Although the ensuing model will treat these times and values as fixed, it must be understood that the subjects of this model are humans who will markedly differ from each other and who will themselves change from episode to episode. Thus, all numbers presented in this treatise must be taken as mean values.)

As an individual approaches the fully rested state, sleep efficiency again begins to drop off. For the sake of the model, this drop-off is quantified as beginning at the point at which the individual has accumulated 80% of the SLUNITS which he needed to achieve full restedness and decreases steadily to zero at full restedness.

The SLUNIT Accumulation (sleep efficiency) curve is shown in Figure 1.

C. SLUNIT Expenditure

SLUNITs (restedness) are expended by activity. The rate of SLUNIT use is, of course, job dependent. Studies consistently show cognitive jobs to be more tiring than rote physical jobs. (Note: It is important not to confuse exhaustion with tiredness. AURA accounts for exhaustion, heat stress and such phenomena in separate algorithms.) Belenky quantifies the loss of acuity due to prolonged employment at a difficult cognitive job (e.g., company commander)

[5]COL Greg Belenky, Walter Reed Army Institute for Research, private communication

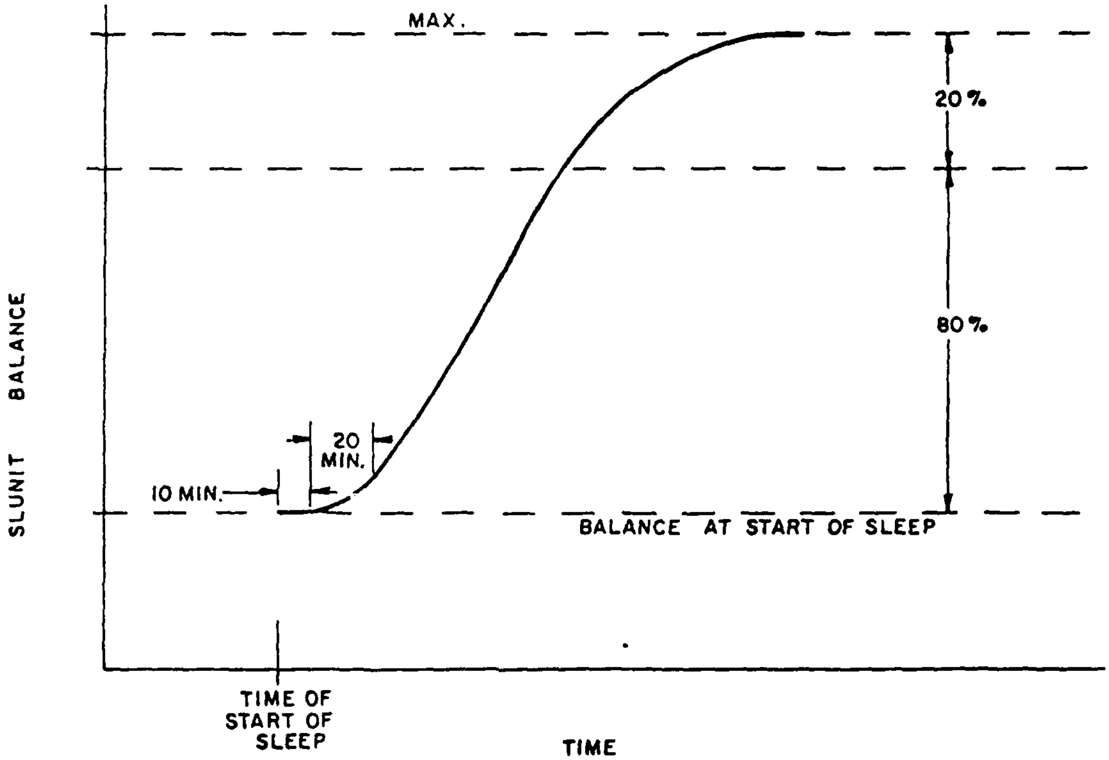

Figure 1: SLUNIT Accumulation (Sleep Efficiency) Curve

at approximately 25% per day. In terms of the AURA algorithm, this corresponds to an expenditure of 380 SLUNITs per day or 0.264 SLUNITs/minute as the "fatigue rate" for the default case.

In AURA, the user has the ability to describe the fatigue rate, in SLUNITs/minute, to be associated with any job. In the course of a run, the SLUNIT balance is maintained for each individual, increasing when he is sleeping and decreasing when he is working at the job-associated rate. This is shown in Figure 2.

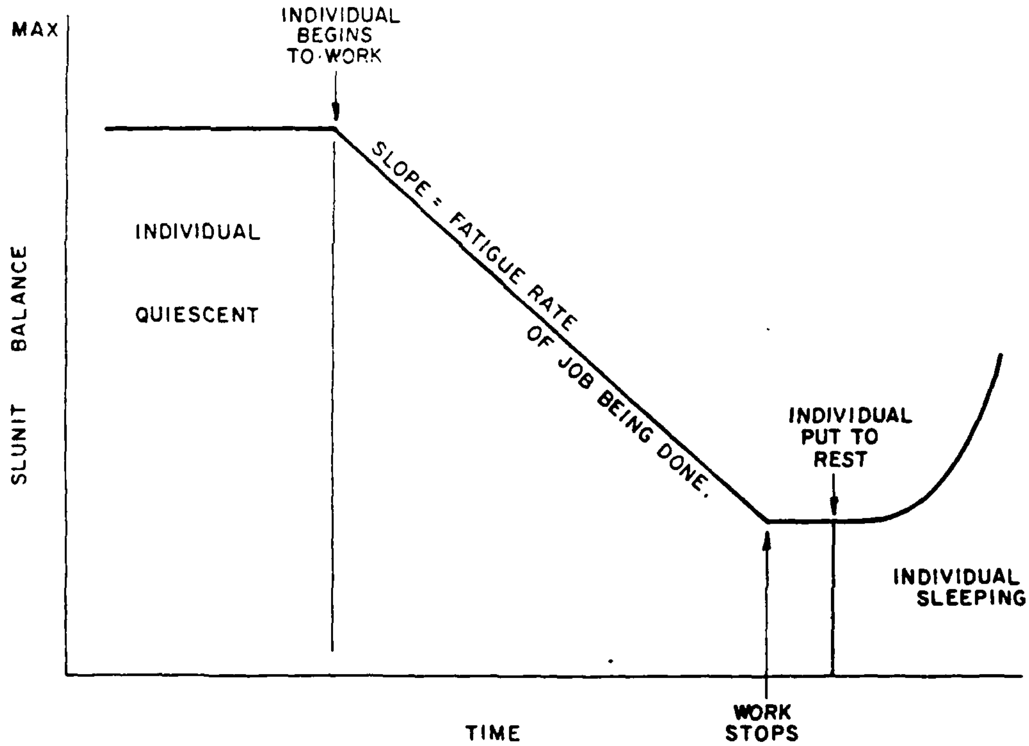

Figure 2: SLUNIT Expenditure and Recovery

D. Fatigue Related Job Performance Degradation

The SLUNIT construct allows AURA to quantify the effects of fatigue by degrading job performance as a function of the SLUNIT balance of the individual performing the job. In all cases, it is assumed that job performance is a linear function of restedness. However, it is noted that some jobs are more demanding and require more acuity than others. This is modeled by establishing, for every job, a SLUNIT demand level. An individual whose SLUNIT balance exceeds the demand level for a particular job suffers no degradation of job performance due to fatigue; below the demand level, job performance goes to zero with the SLUNIT balance. This relationship is shown in Figure 3.

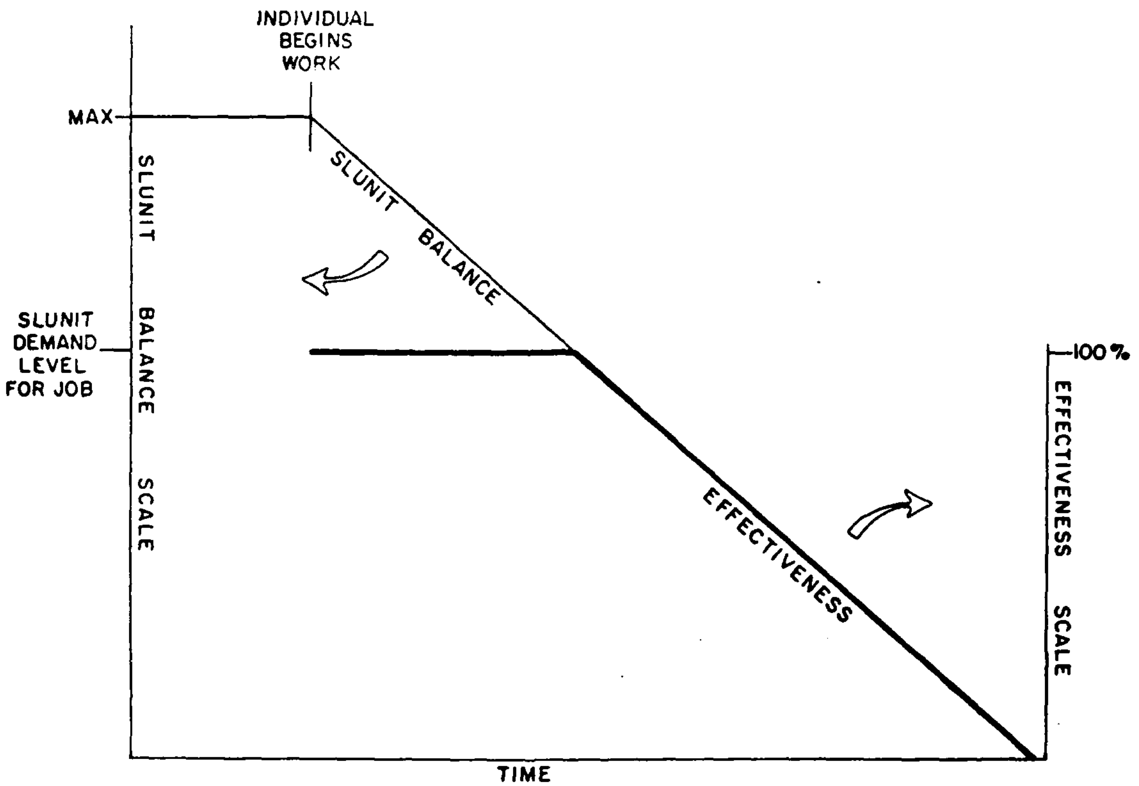

Figure 3: Relationship between SLUNIT Balance and Job Performance.

E. Effect upon AURA Results

The degradation of job performance due to fatigue is multiplicatively combined as an independent factor with other job performance degradation factors in order to evaluate the value of a personnel asset assigned to a job. For example, if an individual were trained to a level of 75% effectiveness in job X, had a radiation sickness decrement of 5% and had a SLUNIT balance of 20% below the job X demand level, his value in job X would be 57% (0.75*0.95*0.8) of that of the fully qualified and operational individual. This value is taken into account by the AURA "Commander" when assigning tasks and evaluating unit performance. Thus, fatigue is fully incorporated in the AURA process, including the logical decision process which leads to the disposition of assets.

In order to allow the user to influence the decision process (thereby modeling the imposition of a sleep discipline), four controls are made available to the AURA user. The first of these is SLUMIN. For each asset, a minimum SLUNIT balance may be specified: any individual reaching that level may not be assigned to any task. Thus, the individual will be unassigned at the end of the asset allocation process and will be put to rest on an "as-available" basis.

The second control is SLUMAX. Each asset may also be assigned a SLUNIT balance above which he may NOT be put to rest. (No rest episode may *begin* above SLUMAX.) This forces availability of individuals until they have worked for a certain period.

The third control is SLPMIN. The user can specify the shortest sleep interval for an individual. Once put to rest, an individual can not be disturbed - except by an incoming round - until SLPMIN minutes have elapsed.

SLUMIN, SLUMAX and SLPMIN are illustrated in Figure 4.

The fourth control is a general control on job assignment. The user has the ability to determine a minimum level of individual effectiveness, below which an asset will not be assigned to a task. Thus, in the example given above, if the user specifies a minimum individual effectiveness of 0.6 for job X, the asset at 0.57 would not be assigned. Therefore, if not assigned elsewhere, the asset will be put to rest on an as-available basis.

In addition, AURA has long provided a number of decision making controls. For example, the user can specify the improvement needed to allow a substitute to replace an available but degraded primary worker. (For example, one can specify the improvement needed to allow a cook to replace a truck driver in the truck driver job.) This control clearly affects the availability of personnel for

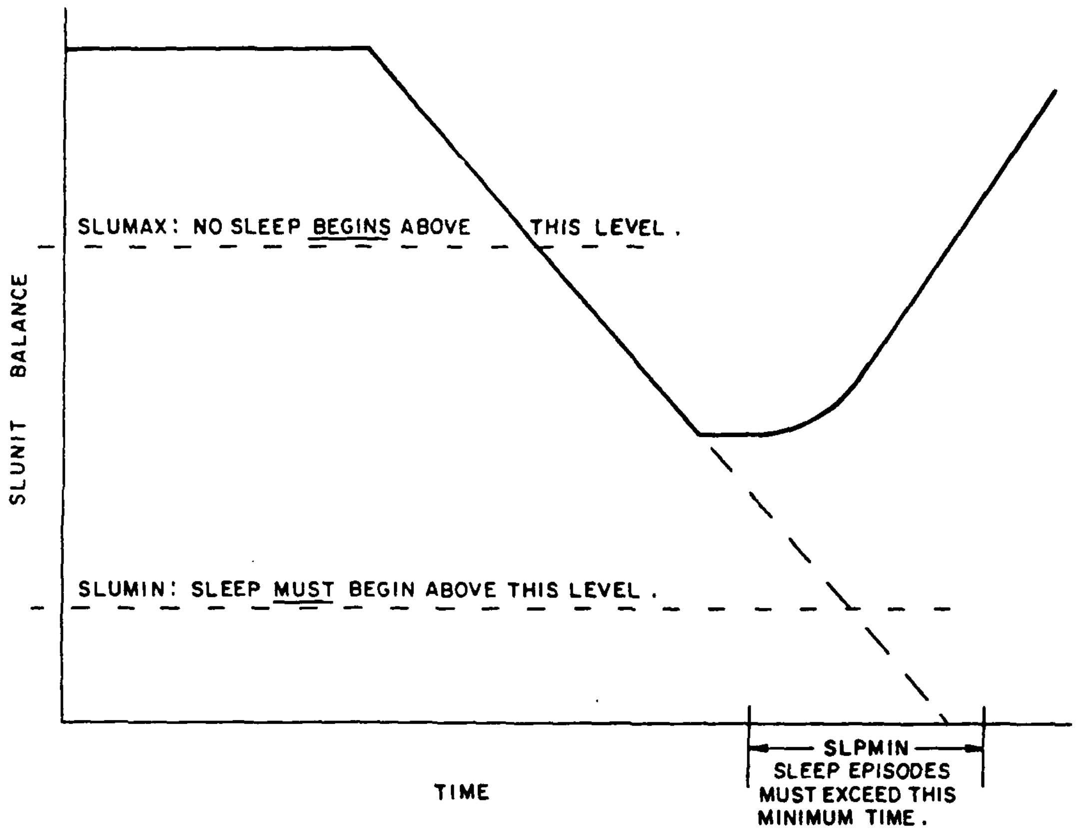

Figure 4: SLUMIN, SLUMAX and SLPMIN

rest assignment. Also, recall that the AURA logic allows the Commander to recognize that the unit performance is being degraded by one malperforming asset and force that asset to rest. Since this decision is controllable by the user, it provides yet another way for the user to input doctrinal responses to the effects of sleep deprivation.

Another user option is the ability to input the starting SLUNIT balance for any individual. This option allows runs to start at an intermediate point in an engagement.

F. Sleep Algorithm Summary

The current sleep algorithm in AURA is a relatively simple model, based upon a growing but, as yet, incomplete data base. Non-linearities have been incorporated into the sleep accumulation portion of the model; however, expenditure of restedness remains a linear function with threshold.

In spite of these shortcomings, the model, when used in conjunction with the other functional models in AURA, has proven to be remarkably accurate in predicting unit performance in extended field tests held at the National Training Center.[6] In addition, the concept of a SLUNIT appears to be a particularly useful construct. With its attendant quantification of restedness, the SLUNIT provides a starting point for developing mathematical expressions to relate sleep and work. The algorithm currently embodied in AURA is a simple example.

[6] Mr. Richard McNally, Science Applications International Corporation, private communication

III. HEAT STRESS MODELING

A. Introduction

In several reports,[7] [8] the BRL methods for evaluating the degradation of job performance due to the wearing of chemical protective apparel were described. In the reports, it was shown that the wearing of chemical protective apparel, commonly called MOPP (mission oriented protective posture) gear, can degrade such physiological factors as fine motor control, near visual acuity and the ability to dissipate metabolically generated heat. In turn, the degradation of physiological factors results in degradation of job performance in a way that reflects the importance and synergistic inter-relationship of the various factors in a particular job.

The modeling of MOPP degradation is greatly simplified by the specific nature of most MOPP effects. For example, the wearing of chemically impervious gloves degrades manual dexterity. but not far vision. Thus, the degrading effect upon job performance due to gloves depends only upon the fine motor requirements of the job and not on more general physical conditions. Unfortunately, this simplistic identification of specific insults with specific requirements breaks down in the case of metabolic heat dissipation. When the MOPP ensemble interferes with the dissipation of heat, job performance is not immediately degraded. Rather, the donning of MOPP gear initiates a chain of time-consuming events related to body heat which are not as immediately noticeable to the individual as are the sudden encumbrance and interference effects of gloves. When a human body is covered, as with MOPP gear, conductive, convective and evaporative heat transfer to the surrounding environment is reduced: This results in an increase in skin temperature, and would, in time, result in an increase in body core temperature. The body attempts to counteract this increase in core temperature by accentuating the mechanisms by which heat is conducted to the skin. Thus, some of the effects of covering a body are increased heartbeat, engorging of the outer blood vessels (manifested as a redness of the skin) and further increased skin temperature. The skin area, in turn, forces more heat to the environment by the slightly increased conductivity and convectivity caused by the increased temperature gradient and, to a much greater extent, by increasing evaporative heat transfer through the

[7] C. H. Wick, J. A. Morrissey and J. T. Klopcic, ***Maintenance Operations in Mission Oriented Protective Posture Level IV (MOPPIV)***, USA Ballistic Research Laboratory report BRL-MR-3629 (October 1987) (UNCLASSIFIED)

[8] C. H. Wick, J. A. Morrissey and J. T. Klopcic, ***Night Reconnaissance Operations in Mission Oriented Protective Posture***, USA Ballistic Research Laboratory report BRL-MR-3628 (October 1987) (UNCLASSIFIED)

increase of area (and volume) of sweat. If these effects are successful, a new equilibrium is established and the body core temperature ceases to increase. The amount of increase and the times involved depend in a complicated way on such factors as environmental temperature, humidity, wind speed and the individual's degree of acclimation and activity. However, it is generally true that: a) until the skin area temperature substantially increases, the body core temperature will increase only slightly; b) the core temperature rise, once begun, will be continuous rather than sudden; and c) the degrading effects of core temperature rise (heat exhaustion and heat stroke) manifest themselves in different people at markedly different threshold body core temperatures and after different elevated temperature duration times.

Another unique characteristic of the heat dissipation impedance effect of MOPP is the ability of the wearer to voluntarily control - within limits - the extent of the problem by reducing the amount of heat that must be dissipated. As seen in Table 1, the mere act of standing generates about 120 watts in an average man; active exercise may generate from 350 to 750 watts. To maintain an equilibrium body core temperature, heat must be dissipated at whatever rate it is generated. Thus, if an individual in a particular environment can only dissipate 300 watts, he can avoid significant core temperature rise by maintaining a work rate which results in a heat generation rate below 300 watts.

Now consider a soldier whose task is to set projectile fuses and then load them into a howitzer. Suppose his work rate is such that he generates metabolic heat at the rate of 350 watts. When the individual dons MOPP gear, his ability to dissipate heat decreases. However, since he also has gloves on, his ability to set fuses is also decreased. He thus spends more time standing (at perhaps 150 watts) and less time at the heavier work rate. It is thus clear that the rate at which a job is performed - and, specifically, the extent to which it is degraded - is inextricably related to the performer's core temperature rise and associated heat casualty probability.

B. Modeling the Phenomenon

As mentioned above, the BRL has developed an algorithm and supporting data bases for the evaluation of job degradation. In order to add the interrelationships of heat casualties, two extensions were required: 1) a model of body core temperature versus time as a function of work rate, MOPP gear thermal characteristics, and environment, and 2) an estimation of heat casualty probability as a function of core temperature and time.

Table 1: Energy Expenditure as a Function of Activity

MILITARY TASKS

Form of Activity	kcal/hr/man	watts/man
Sleeping	65	76
Sitting at Rest	100	116
Standing Relaxed	105	122
Rifleman Resting	132	153
Light Exercise (Driving a Vehicle)	170	198
Rifleman on Patrol	225	262
Active Exercise (Loading a Cannon)	300	349
Severe Exercise (Assault)	450	523
Fire Fight	480	558
Running (5.3 mph)	570	662
Very Severe Exercise (Running with a Load)	600	697
Walking Very Fast	650	755

* - Taken in part from R.F.Goldman, "Energy Expenditure of Soldiers Performing Combat Type Activities", Ergonomics, 8 (3),321 (1965)

COMMON (CIVILIAN) ACTIVITIES

Form of Activity	kcal/hr/man	watts/man
Cooking	100	116
Easy Walking	250	291
Badminton	250	291
Brisk Walking	300	349
Tennis	300	349
Skating	300	349
Slow Jogging	300	349
Bicycle Riding	380	442
Aerobic Dancing	385	447
Slow Running (3.5 mph)	400	465
Soccer	400	465
Sawing Wood	500	581
Swimming	500	581
Snow Skiing	500	581
Running (7.5 mph)	650	755
Competitive Swimming	650	755
Weightlifting	650	755

C. Body Core Temperature versus Time

To estimate body core temperature versus time, the widely accepted Goldman Heat Stress Model[9] was used. The Goldman model, based upon human and mechanical heat dissipation experiments, relates body core temperature versus time to such parameters as metabolic rate, atmospheric temperature and humidity, wind speed, skin temperature and area, and clothing ensemble heat flow impedance parameters (see Table 2). The Goldman model is mathematically summarized in the literature.[10] The equations from ED-SP-75011 were used to form the basis of an interactive utility program, TCORE. Written in FORTRAN-77, TCORE prompts the user for values for the input parameters. It then returns a synopsis of the inputs, and prints out calculated values for equilibrium core temperature, lag time before temperature rise, characteristic rise time of temperature, and a probability of heat casualty (discussed below). Finally, to aid in sensitivity searches, TCORE allows interactive changing of specific parameters and rerunning.

As an example, consider an individual whose task normally required a metabolic expenditure of 350 watts (active exercise in Table 1). However, because of the impedance of his visual and tactile faculties, the individual can perform his task at *0.6 of his basic rate*. Allowing 120 watts as his personal sustenance or "overhead", the performance of the task itself used 350-120 = 230 watts. Degraded performance then requires (230 x 0.6) + 120 = 250 watts. Assume further that the atmospheric temperature is 80 $\deg F$, humidity 80 percent, and the code's default values for skin temperature and area, and wind parameters are acceptable. From Table 2, the heat impedance values for *clo* and i_m/clo are chosen to be 2.50 and 0.11, respectively. With this information, TCORE predicts an equilibrium core temperature of 102.2 $\deg F$, a lag time of 14 minutes before the core temperature begins to rise and a rise time of 75 minutes.

[9] R.F. Goldman, *Environment, Clothing, and Personal Equipment, and Military Operations*, US Army Research Institute of Environmental Medicine, Natick, MA, 1974 (UNCLASSIFIED)

[10] Staff, *A Computer Program to Predict Energy Cost, Rectal Temperature, and Heart Rate Response to Work, Clothing and Environment*, Edgewood Arsenal Special Publication ED-SP-75011 (UNCLASSIFIED)

Table 2: Clothing Insulation and Evaporative Impedance

Uniform	*clo*	i_m/clo
None	0.78	0.75
Coveralls, lightweight, standard cotton	1.29	0.39
Jacket and trousers (fatigues)	1.33	0.37
Old utility uniform (8.5 oz.)	1.56	0.31
New utility uniform (8.2 oz.)	1.40	0.34
Combat uniform, tropical	1.43	0.34
CB overgarment, alone	1.64	0.27
CB liner, standard	1.65	0.26
CB overgarment over combat tropical	2.11	0.23
CB overgarment over new utility	2.07	0.22
CB overgarment over CB liner	2.15	0.22
1/4 length plastic raincoat over fatigues	1.45	0.28
1/2 length plastic raincoat over fatigues	1.48	0.24
3/4 length plastic raincoat over fatigues	1.62	0.20
Full length plastic raincoat over fatigues	1.70	0.16
Standard poncho over fatigues	1.83	0.11
Add: For protective mask,hood and gloves	+0.25	-0.07
Add: For armored vest	+0.15	-0.04
Add: For mask, hood, gloves and vest	+0.40	-0.11

* - Taken from R.F. Goldman, ***Systematic Evaluation of Thermal Aspects of Air Crew Protective Systems,*** AGARD Conference Proceedings No. 25, Behavioral Problems in Aerospace Medicine, October, 1967, Rhode-Saint-Genese, Belgium

D. Heat Casualty versus Core Temperature

Unfortunately, little work has been published on the relationship between body core temperature and heat casualties. It is known[11] that heat stroke (catastrophic thermal damage of the brain) occurs in different individuals in the range of $106 - 108\,\deg F$. However, interference with mental processes, resulting in confusion, erratic behavior, and shut-down of the body cooling system with a resulting cataclysmic temperature use, may begin around 104 $\deg F$.

On the other hand, for the purpose of modeling individual performance, it is not necessary for a casualty to be fatally afflicted. At core temperatures below 102 $\deg F$, especially when accompanied by fluid loss and electrolyte imbalance, some individuals will begin to manifest the incapacitating symptoms of heat exhaustion: headache, dizziness, vomiting, weakness, rapid pulse and breathing, and severe cramps. As in the case of heat stroke, the variations in susceptibility to heat exhaustion, even among uniformly, highly motivated troops, are important and complex.

In order to include the heat casualty phenomena in their CHEMCAS model, the BDM Corporation has proposed a simple, linear algorithm for predicting heat stress probability as a function of core temperature.[12] Based upon data from Goldman, BDM equated casualty probability to 0.0 at 101 $\deg F$ increasing linearly to 1.0 at 106 $\deg F$. This curve was compared to heat casualties and associated rectal temperatures experienced in a battalion level field test[13] with fair agreement. Awaiting publication of a more substantiated prediction of heat stress casualties, we have adopted the BDM linear equation.

E. Incorporation of Job Performance Degradation and Heat Stress into Combat Models

Using the job performance degradation model and the heat stress probability model described above, the BRL produces correlated sets of parameters to account for the detrimental effects of wearing MOPP gear. For each job, the degradation parameters are:

[11] Dr. R. Mosbar, USA Academy of Health Sciences, Ft. Sam Houston, TX, private communication

[12] BDM Services Co, *Techniques for War Game Assessments of Chemical Operations*, BDM/CARAF-FR-75-033, 1975 (UNCLASSIFIED)

[13] *ROAD Battalion Operations in a Toxic Environment*, Vol 2 of 3, *Toxic Free Operational Capability Experiment*, US Army Combat Developments Command, Experimentation Center, (AD 371766), Ft. Ord, CA., (Dec 1963) (UNCLASSIFIED)

f_1 : Fraction of NO-MOPP Rate

f_2 : Fraction of NO-MOPP Accuracy

$PCAS$: Probability of heat casualty

t_{LAG}: Time before onset of temperature use

τ : Characteristic rise time

It remains to develop an algorithm which will use these parameters to realistically portray MOPP degradation/heat stress in AURA. (Such an algorithm would also be useful in wargame simulation models such as JANUS and BATTLE.[14]) The use of f_1 and f_2 to model performance degradation has previously been defined.[15] We therefore proceed to define an algorithm for modeling the occurrence of heat stress casualties.

Since, as discussed above, there is very little firm data on the complex problem of predicting heat stress casualties, a detailed mathematical model is unwarranted at this time. However, certain characteristics of the phenomenon are known and should be reflected in this model:

1. Casualties are probabilistic; i.e., only a fraction of personnel will become casualties. The probability depends upon core temperature.
2. The time of commencement of casualty status is a random variable; i.e., among those who become heat casualties, the time of loss will vary.
3. Heat casualties result, at least partially, from increased core temperature. Therefore, the probability of loss vs. time function should initially lag the core temperature vs. time.

The simple linear algorithm used in AURA satisfies these characteristics.

First, the BDM model was adopted to predict the probability that any specific individual will become a casualty. Since this probability is based upon his projected equilibrium core temperature, this satisfies characteristic (1).

The probability of occurrence was augmented with a probabilistic time-of-occurrence function which was derived as follows. From reference 6, the time

[14]Mr. William Leach, US Army TRAC-WSMR, White Sands Missile Range, NM, private communication

[15]CANE FDTE Chemical Modeling Working Group meeting held at TRASANA, WSMR, NM, 25-27 Jan 83

profile of temperature can be approximated by a delayed exponential of the form shown in Figure 5. Therefore, the shape of the time probability function must be such that no casualties occur until after t_{LAG} has passed; then the probability of casualty rises to a maximum of PCAS in the time characterized by the exponential parameter τ. A simple, step-wise linear function that approximates such behavior is shown in Figure 5. This is the function used in AURA.

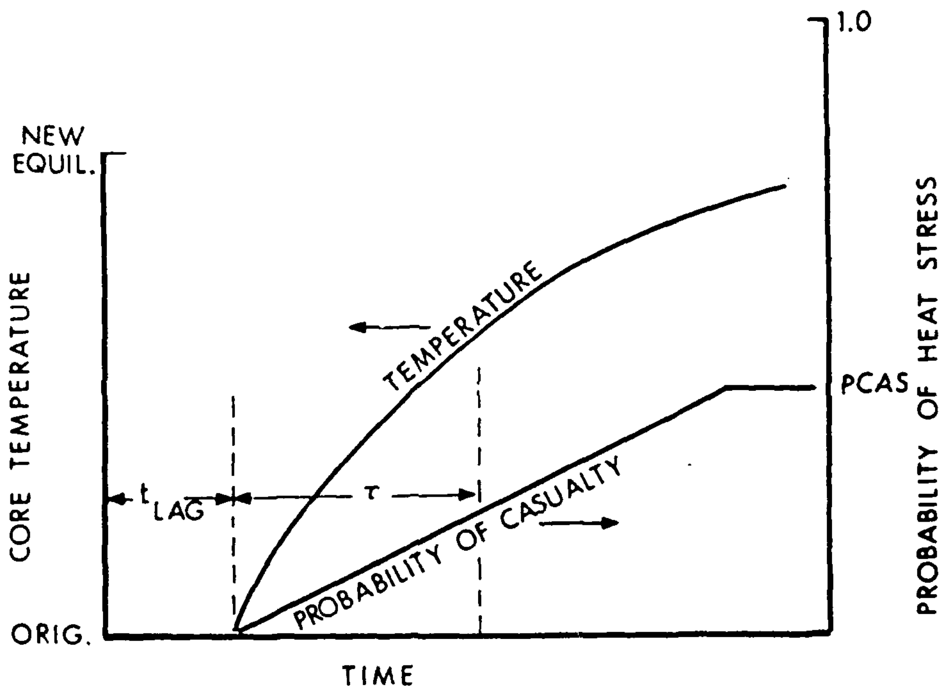

Figure 5: Core Temperature and Probability of Casualty versus Time in AURA

In order to satisfy characteristic 2, the heat casualty probability function must be stochastically sampled. AURA uses the following algorithm.

Every time an individual gets into MOPP gear, a random number, RN, is drawn for that individual. If RN is larger than PCAS, the individual will not

become a heat stress casualty. If the value of RN is less than PCAS, that individual's t_{CAS} is set to

$$t_{CAS} = t_{LAG} + 2 * \tau * RN/PCAS + t_{CLOCK} \tag{1}$$

where t_{CLOCK} is the time in the simulation of donning MOPP. The run then proceeds.

At each subsequent run time, t_{CLOCK}, the value of t_{CAS} for each individual is compared against t_{CLOCK}. If t_{CAS} is less than t_{CLOCK}, the individual is a casualty.

Upon getting out of MOPP gear (unMOPPing), the individual's t_{CAS} is reset to infinity, indicating that no risk of heat casualty exists.

F. Verification of the Heat Stress Algorithm

There exist little data upon which verification of a heat stress algorithm can be based. Fortunately, in a hot climate study, Joy and Goldman [16] recorded a sufficient number of heat casualties to develop a predicted time to 50% heat casualties. The summary figure from their report is reproduced here as Figure 6.

As a verification of the AURA heat stress methodology, input parameters were developed to model the conditions prevalent in the Joy and Goldman study. Appendix B details the development of those parameters and the subsequent results. Figure 7, taken from Appendix B, is presented here for comparison. It is seen that, with the exception of the open suit, light work point at a wet bulb globe temperature of 95 deg F, the AURA heat stress model predictions are remarkably close. These data confirmed the acceptability of the model.

G. Summary of the Heat Stress Algorithm

The preceding algorithm has shortcomings, in addition to those occasioned by the lack of basic data. For example, it is known that core temperature does not decrease immediately upon unMOPPing. In fact, if unMOPPing occurs before the new core temperature equilibrium has been reached, studies have shown

[16] R.J.T. Joy and R.F. Goldman, "A Method of Relating Physiology and Military Performance: A Study of Some Effects of Vapor Barrier Clothing in a Hot Climate", Military Medicine, Vol. 133, No. 6, (June 1968) (UNCLASSIFIED)

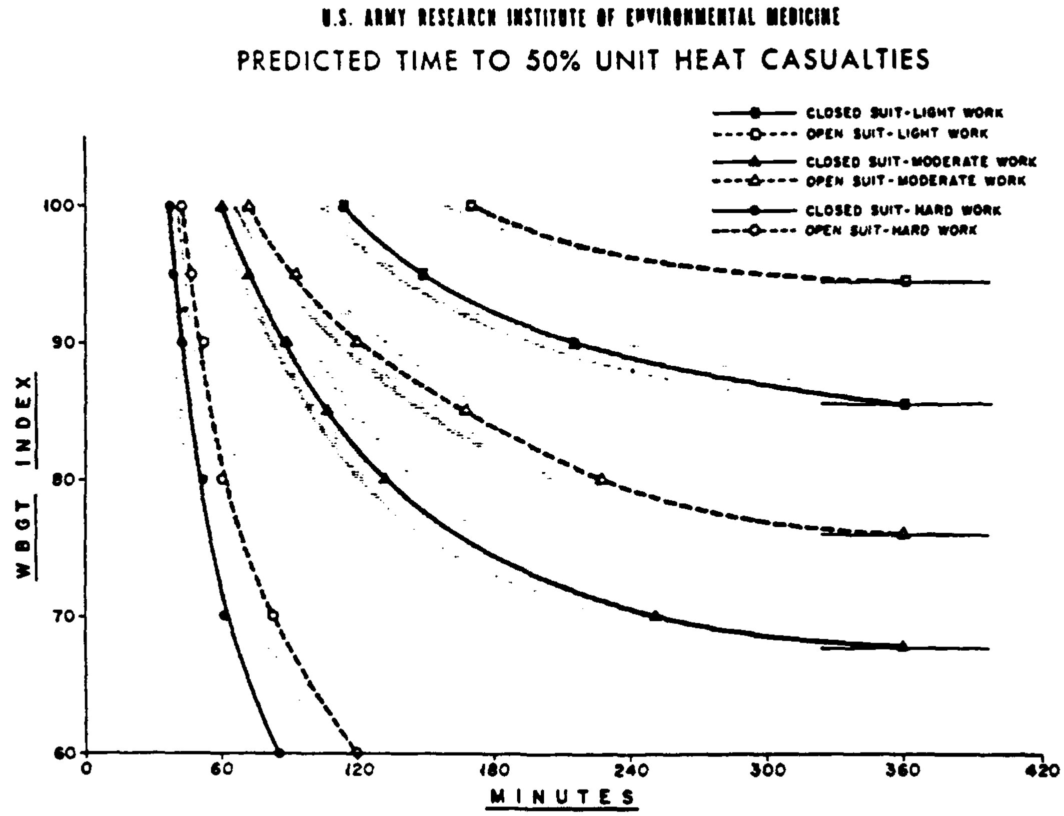

Figure 6: Predicted Time to 50% Unit Heat Casualties from Joy and Goldman

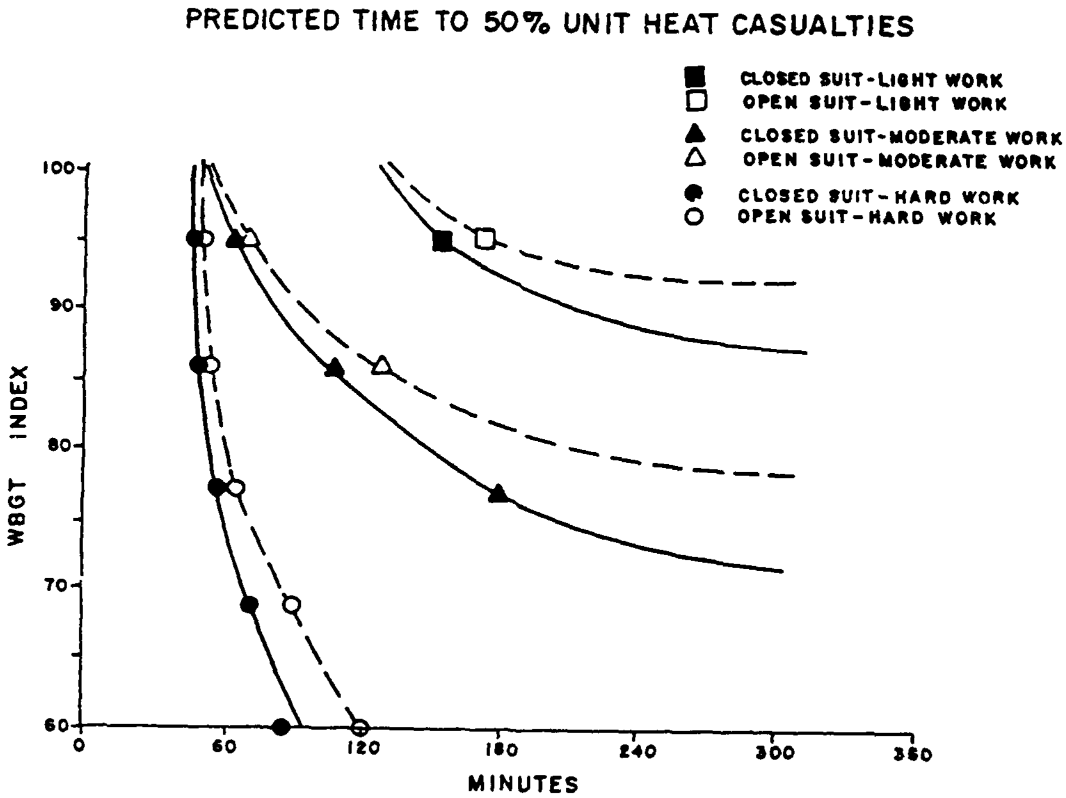

Figure 7: Predicted Time to 50% Unit Heat Casualties from the AURA Heat Stress Model

that the core temperature may continue rising for minutes before beginning to decrease. Presumably, this phenomenon implies a risk of heat stress after unMOPPing, which is ignored in the current algorithm.

This algorithm also ignores several heat-related phenomena which certainly affect heat stress casualty probabilities. For example, this algorithm assumes that all bodily needs are met, including sufficient water and salt to replace sweat losses. An individual who "survives" the draw against PCAS could apparently remain in MOPP forever! Clearly this is an incomplete model. Fortunately, scientists at ARIEM are developing a more complete model of heat stress probability versus time-in-MOPP as a function of a number a factors in addition to core temperature.

On the other hand, the current algorithm has several very good features. In spite of its simplicity, it meets the three basic criteria set forth in the preceding section. Furthermore, the parameters upon which it is based can be calculated off-line using state-of-the-art methodologies and data. Thus, technical advances, either in material changes (better MOPP gear) or in physiological understanding can easily be reflected through inputs.

The method of drawing for t_{CAS} has a number of advantages. For example, correlated phenomena and conditional probabilities, which are not practical to play if casualties are drawn at each new time step, can be straightforwardly added to this technique. Since the number of individuals is not too large, this technique - by drawing only once per individual - makes the generally beneficial trade of a small amount of storage for a fair amount of computer time.

Perhaps most importantly, the generation of PCAS, t_{LAG} and τ are independent of their use in AURA. Hence, any model whose output can be interpreted in terms of a probability of occurrence and probabilistic time can replace TCORE and the BDM model as an input generator for AURA. Thus, forthcoming ARIEM models have ready applications. Meanwhile, numerous studies[17] have used the TCORE program for generation of PCAS, t_{LAG} and τ, and recent studies for the Office of the Surgeon General have used empirical results to generate those parameters.

[17]L.K. Roach et al, US Army Ballistic Research Laboratory, private communication

IV. SUMMARY

The fatigue and heat stress models described in this report have been extensively used since their incorporation into AURA in 1984. Recent data and studies have resulted in updating the parameters of the models; the underlying assumptions and functional forms have remained intact. Comparison of the predictions of the models with data taken at large field exercises and studies have confirmed the accuracy both of the models and of their interface with the rest of the AURA methodology.

Appendix A

Derivation of Fatigue Defaults

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As with most algorithms in AURA, the fatigue algorithms were written to allow user input of important parameters. (Several of the adjustable parameters were discussed in Section II., above.) However, to expedite use of the algorithms in studies that are not concerned with the details of fatigue, it is necessary to supply AURA with a set of default values for the parameters. Since the evaluation of default values further illustrates the roles of the parameters, that evaluation is presented in this appendix.[18]

Parameter evaluation requires a set of data as a basis. In this case, three fixed points were used:

1. An "equilibrium" can be reached at 18 hours work per 6 hours sleep.
2. A fully rested individual can work 18 hours before his work begins to degrade (due to fatigue - not exhaustion)
3. The performance of a fully rested individual will go to zero in four days if he is not allowed to rest.

The creation of a fatigue algorithm required the definition of the unit of measure in terms of which fatigue and restedness could be quantified. This definition effectively provided a fourth datum for evaluation of the default parameters.

4. An individual gains 1 SLUNIT (SLeep UNIT) from one minute of *efficient* sleep.

Note: Items 1 and 2 imply that a fully rested individual can maintain 100% performance if rested six hours per day.

The above four data are sufficient to fix the parameters of the fatigue algorithm. First, referring to Figure A-1, one can calculate the benefit to be derived from six hours of rest.

[18]The following calculation was first done in conjunction with Mr. Richard McNally, Science Applications International Incorporation.

The first 10 minutes	⇒	0 SLUNITs
The next 20 minutes	⇒	10 SLUNITs
The next 217 minutes	⇒	217 SLUNITs
The final 113 minutes	⇒	57 SLUNITs

Note that the SLUNITs (57) gained at 50% efficiency in the final block of time (113 minutes) constitutes 20% of the total (284) needed for full restedness, as prescribed by the SLUNIT accumulation curve.

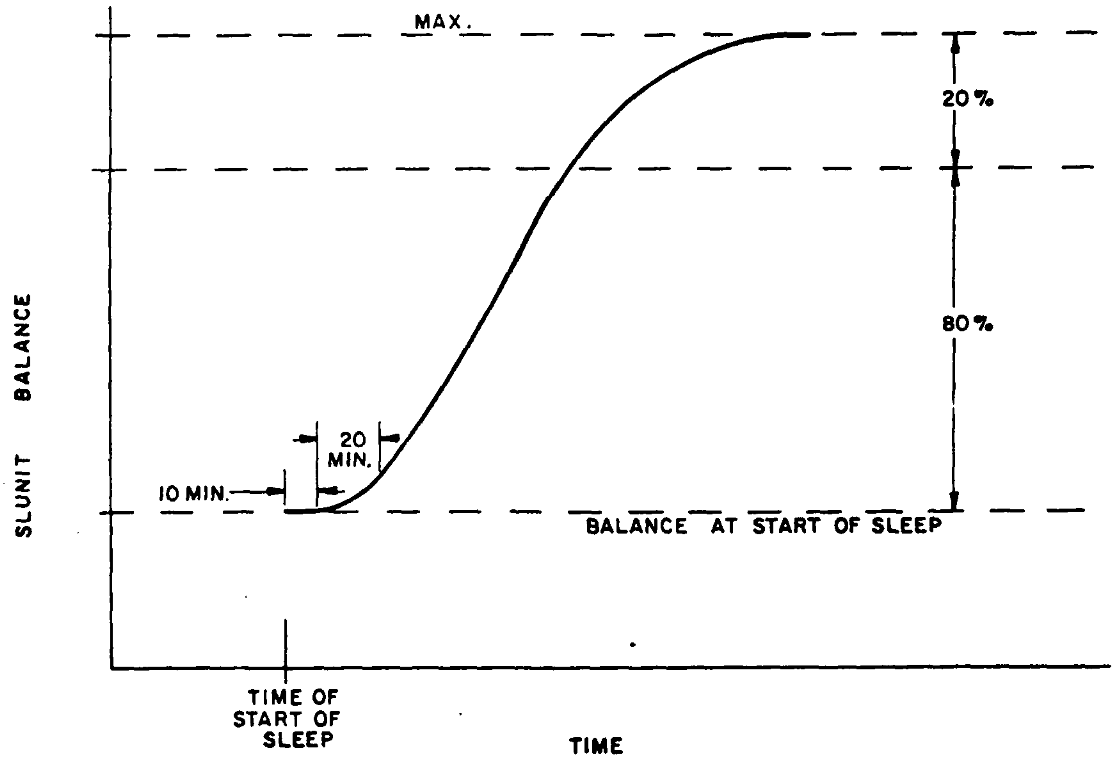

Figure A-1: **SLUNIT Accumulation (Sleep Efficiency) Curve**

(For convenience, at this point, we "rounded" the SLUNITs needed to 285.)

Next, in accord with datum 1, the SLUNITs gained in 6 hours are equal to that used in 18. Therefore, the default fatigue rate, FR, is given by

$$FR = 285/(18 * 60) = 0.264\ SLUNITs/minute$$

Next, we can place "full restedness" on an absolute SLUNIT scale through datum 3. Since 4 days of work results in total depletion of SLUNITs, full restedness (CEILING) must be:

$$CEILING = 4(da)*1440(min/da)*0.264(SLUNIT/min) = 1520\, SLUNITS$$

Finally, using datum 2, we can evaluate a default value for the threshold for degradation. Since the performance begins to degrade after 18 hours work, which we have shown to consume 285 SLUNITs, the threshold for task degradation (SLUNOP) is given by

$$SLUNOP = 1520 - 285 = 1235\ SLUNITS$$

As an independent (extreme) check on the predictions of this algorithm, we can now estimate the rest time needed for an individual who has become totally fatigued (4 days of solid work) to recuperate. Assuming he needs to replenish all 1520 SLUNITs, the rest required is calculated as follows.

The final 20% (304 SLUNITS)	$\Rightarrow$	608 min
The first 10 min (0 SLUNITS)	$\Rightarrow$	10 min
The next 20 min (10 SLUNITS)	$\Rightarrow$	20 min
The remaining 1206 SLUNITS	$\Rightarrow$	1206 min
Total	$\Rightarrow$	1844 min = 31 hours

Considering the extreme extrapolation required by this calculation (a ***totally*** fatigued individual) and the tremendous variability among individuals, a predicted mean value of 31 hours was considered reasonable. We therefore installed the default values in AURA with reasonable confidence that the casual user experiences reasonable behavior from the fatigue algorithm.

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Appendix B

Verification of the AURA Heat Stress Algorithm

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In a hot climate test, Joy and Goldman[19] were able to develop predictions for the time at which a unit would reach 50% unit heat casualties as a function of the unit work rate, clothing ensemble (open or closed) and the wet bulb globe temperature (WBGT) index. Their results are summarized in Figure B-1. It was of interest to compare the predictions of the AURA heat stress model, using TCORE, to these results.

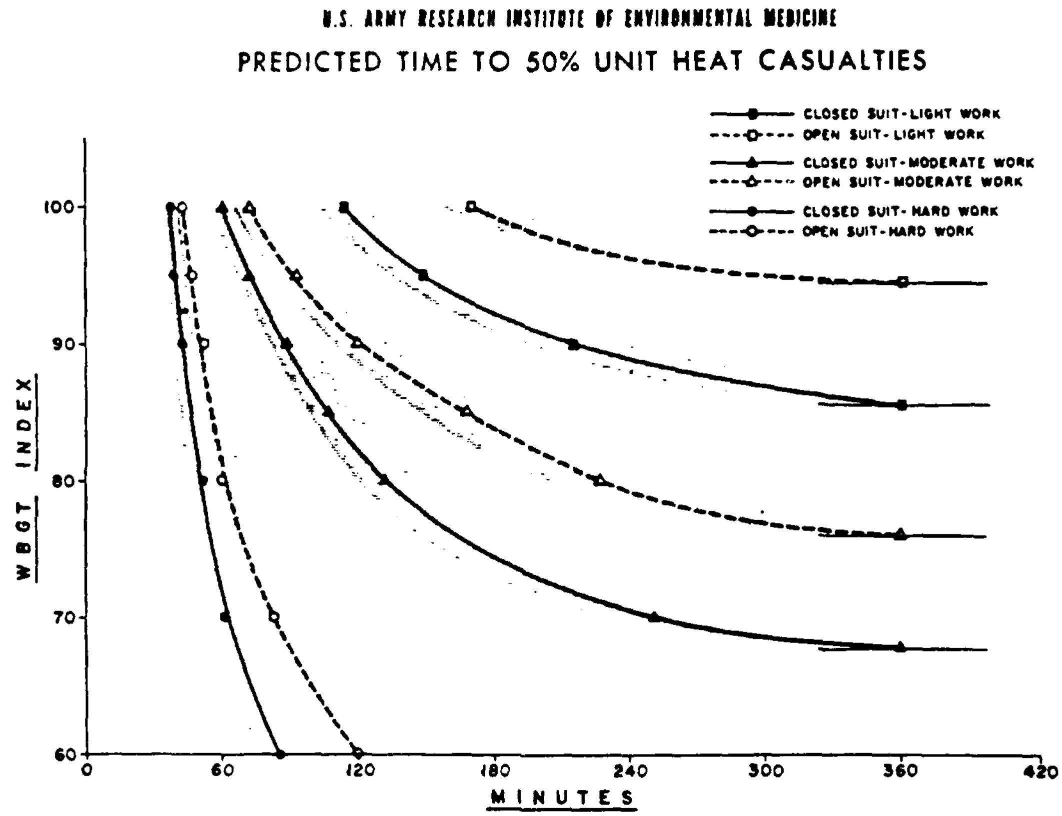

Figure B-1: Predicted Time to 50% Unit Heat Casualties from Joy and Goldman

To make the comparison, two dissimilarities had to be reconciled. First, AURA uses probability of casualty and a probabilistic time-to-casualty rather than

[19] R.J.T. Joy and R.F. Goldman, "A Method of Relating Physiology and Military Performance: A Study of Some Effects of Vapor Barrier Clothing in a Hot Climate", Military Medicine, Vol. 133, No. 6, (June 1968) (UNCLASSIFIED)

predicting the time to 50% of unit loss. This difference was resolved by deriving the AURA parameters (PCAS, t_{LAG} and τ), mathematically constructing the probability of casualty versus time curves (see Figure B-2) and solving each for the time at which the probability of casualty reached 50%. As environmental conditions or energy dissipation become less severe, time to heat stress becomes longer - eventually becoming infinite (no heat stress). This showed up in AURA as cases for which PCAS did not reach 50%.

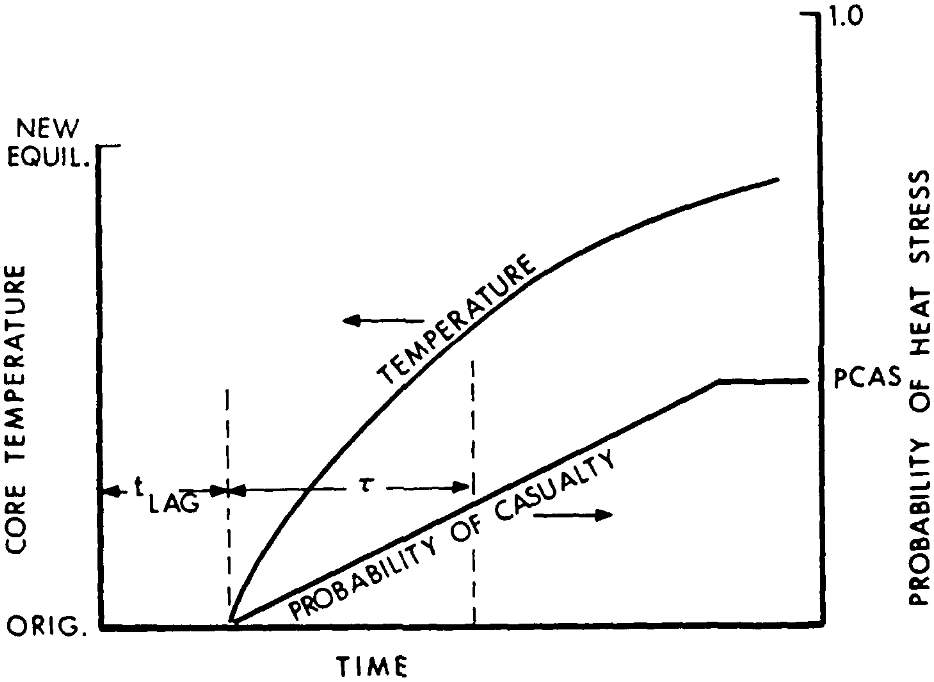

Figure B-2: Core Temperature and Probability of Casualty versus Time in AURA

Significantly more difficult was the relation of WBGT to TCORE environmental parameters. Recall, WBGT is defined as the weighted sum of three temperatures:

$$WBGT = 0.7WBT + 0.2BGT + 0.1T \quad (2)$$

where WBT is the wet bulb temperature, BGT is the black globe temperature and T is the customary atmospheric temperature. To equate WBGT to T and relative humidity (rh), two assumptions were made. First, we assume that the environmental equations in TCORE, which account for the solar load, will account for the difference between the black globe temperature and T. Thus, we set BGT = T.

Next, WBT was related to rh and T by an equation of the form:

$$rh = 100 - C_1 \times \frac{(T - WBT')}{(T + C_2)} \tag{3}$$

where C_2 is expressed in deg C. Using values of WBT from the CRC tables [20] the fitting parameters, C_1 *and* C_2, were found to be:

- $C_1 = 235.4$
- $C_2 = 10.4$ deg C

Solving the rh equation for WBGT and substituting for WBT we have:

$$T = \frac{WBGT + 0.7C_3C_2}{0.7(1 - C_3) + 0.3} \tag{4}$$

where

$$C_3 = \frac{(100 - rh)}{C_1} \tag{5}$$

TCORE was then run for several combinations of rh and T corresponding to the WBGT points in Figure B-1.

[20] C.D.Hodgman, ed.,*Handbook of Chemistry and Physics,* 44th Edition, The Chemical Rubber Publishing Co., Cleveland, OH (1963) (UNCLASSIFIED)

Other parameters of interest were:

	Open Clothing	MOPPIV
clo	2.25	2.4
i_m/clo	0.17	0.13

	LIGHT WORK	MODERATE WORK	HEAVY WORK
Energy (watts)	200	300	450

The resulting TCORE/AURA predicted times to 50% unit heat casualties are shown in Figure B-3. Comparing these to those measured/extrapolated by Joy and Goldman, the agreement is seen to be exceptional for the severe conditions and quite good for all conditions except the least severe (open suit, light work). Since the predicted and measured times are so long for the least severe conditions (from three to six hours), the high likelihood of interfering factors makes heat stress evaluation in such conditions an extremely inaccurate and ill-defined process. We thus conclude that the TCORE/AURA model for prediction of heat stress casualties is in good agreement with the available data and can thus be used with confidence in AURA analyses.

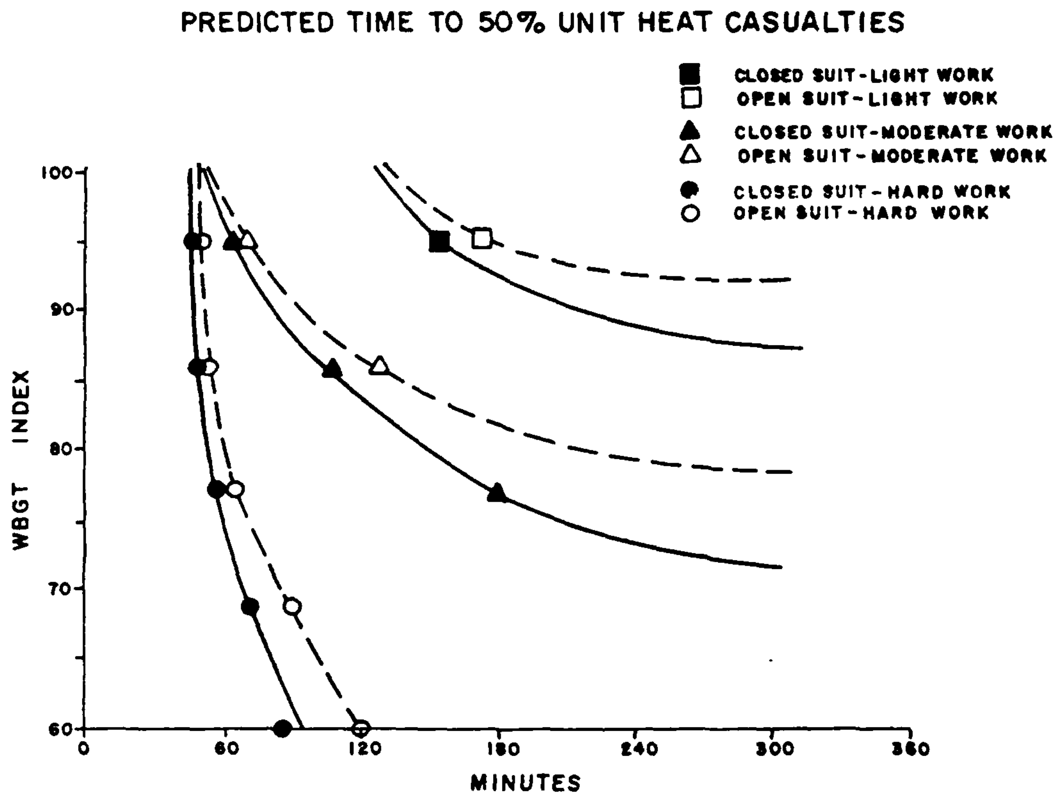

Figure B-3: **Predicted Time to 50% Unit Heat Casualties from the AURA Heat Stress Model**

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